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THE ASSESSMENT OF TRANSIENT VIBRATION WITH RESPECT TO HUMAN EXPOSURE

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ABSTRACT

This report reviews two procedures for evaluating the vibration ride-quality of vehicles. The first is based on the current International Standard (ISO 2631). The second is a procedure for evaluating impulse vibration. It is based on Payne's model for determining the peak spring strain in the human spine and on Allen's proposed specification for human tolerance to repeated shocks. An electronic analogue of Payne's model was developed to produce values of the Dynamic Response Index (DRI) from successive peaks in the acceleration-time history of a z-axis vibration signal, and Allen's comfort and injury criteria when applied to the accumulated DRI exposure. Three Canadian Forces vehicles were studied: (1) M113 APC driven at 20 kph across country; (2) five-quarter ton truck at 50 kph, rough pavement; and (3) Centurion Tank at 12 kph, cross country. It was concluded that more data are required on the observed effects of human exposure to mechanical shocks, particularly when they occur at relatively low intensities, before the DRI/Allen procedure can be used as a robust method to assess human tolerance to such shocks. Although both the DRI/Allen procedure and ISO Standard 2631 ranked the three vehicle/surface conditions in the same order, studies involving a much wider variety of conditions should be conducted to determine possible differences between the two.

INTRODUCTION

The existing method of evaluating steady-state vibration, International Standard (ISO) 2631 (1), is based on analysis of the rms (root-mean-square) levels of acceleration. However, rms measures may not be appropriate when the motion of a vehicle includes transient vibration (mechanical shocks), as experienced in road or all-terrain vehicles during travel on broken pavement or cross-country, or in high-speed marine surface-effect craft due to the "slamming" of the hull against wave flanks.

A technique has been proposed for quantifying such shocks, based on the Dynamic Response Index (DRI)(2) and associated exposure criteria. This report reviews the basis for the ISO 2631 and DRI procedures, presents the results of an analysis of the vibration observed in three military vehicles using both criteria, and discusses their appropriateness to the analysis of vehicle-ride quality.

EVALUATION OF NON-IMPULSIVE VIBRATION

To predict the effects of mechanical forces upon the human body, it is necessary to quantify its biodynamic response characteristics. Pioneering work in support of this was carried out in the 1930s by von Bekesy, who determined the driving point impedance of the body under applied vertical vibration, and in the 1950s by Dieckmann, who derived a single mass-spring-damper model of the body (3).

It was accepted by early workers that relatively simple dynamic models would be adequate for interim engineering purposes, once the correct spring rates and damping coefficients were determined. The overall tolerance curve for the human body, proposed by von Gierke and Coermann (4) in 1963, fulfilled this requirement. The envelope of the curve was formed from the responses of three simple body sub-system models (spine-abdomen, lumbrosacral, and head), and was accepted as the basis of the z-axis vibration-tolerance curve in ISO 2631.

In 1976, Payne (5) proposed a definitive model comprising three parallel mass-spring-damper sub-systems (visceral, spinal, and body vibration) with associated tolerance criteria. A typical limit (one hour) generated by the model for sinusoidal vibration is shown in Figure 1. The overall response curve of the model is the envelope of the curves of limiting acceleration for each sub-system (indicated by the hash marks), and indicates that the visceral model limits exposure up to about 4.6 Hz, and the spinal model up to 11.7 Hz. Above about 50 Hz, the exposure limit set by the body model is coincident with the ISO 2631 one-hour Exposure Limit.

The guidelines contained in ISO 2631 specify rms acceleration limits for vibration in the frequency range 1 to 80 Hz in terms of three criteria: (a) the preservation of working efficiency, designated at the "fatigue-decreased proficiency" (FDP)

boundary, (b) the preservation of health and safety, the "exposure limit" (EL), and (c) the preservation of comfort, the "reduced-comfort" (RC) boundary.

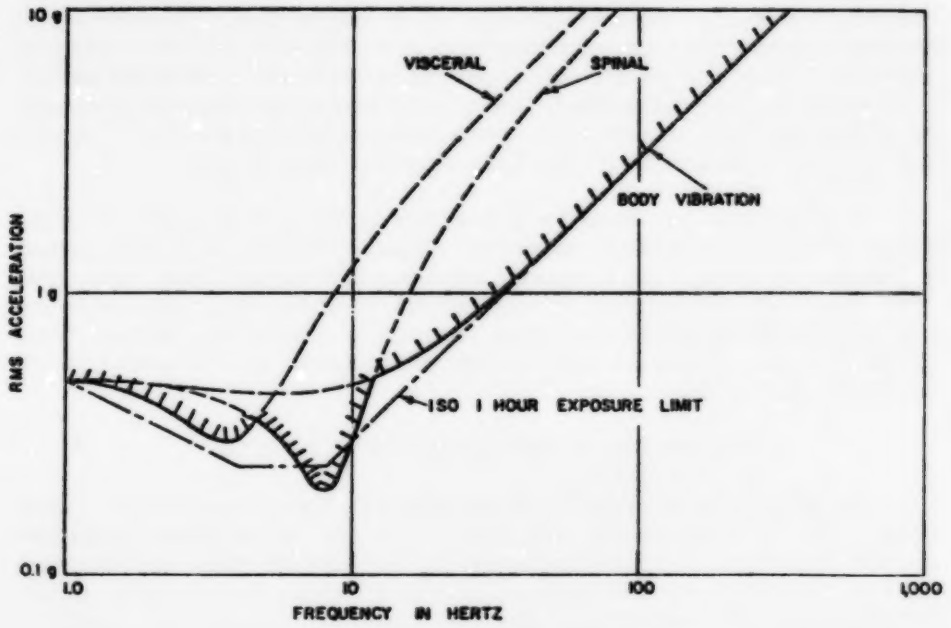

FIGURE 1. Frequency response of the three mass-spring-damper systems (visceral, spinal, and body vibration) of Payne's ride-comfort model, for sinusoidal vibration, permitting "severe but tolerable - less than one-hour exposure" (After Payne (5)). Shown also is the ISO 2631 z-axis one-hour Exposure Limit.

The fatigue-decreased proficiency boundary specifies a limit beyond which exposure to vibration may produce a significant reduction in working efficiency for many types of tasks, particularly tasks in which time-dependent effects such as fatigue are known to worsen performance.

The exposure limit is 6 dB (twice the rms acceleration) higher than the FDP boundary. It is set at approximately one-half the level considered to be the threshold of pain (or limit of voluntary tolerance) for healthy subjects restrained to a vibrating seat. The reduced-comfort boundary lies 10 dB below (one-third the rms acceleration level) the FDP boundary, and in the transportation environment, is related to the difficulty encountered in carrying out activities such as reading, writing, eating etc.

The vibration evaluation method recommended in the first edition of ISO 2631 applied to non-impulsive accelerations; i.e., acceleration waveforms with crest factors (ratio of peak to rms levels) not greater than 3.0 (6). In an amendment to the second edition, this limit was increased to 6.0 (1).

EVALUATION OF IMPULSIVE VIBRATION

Early work on human tolerance to acceleration impulses was carried out during the Second World War by Germans working on the development of aircraft escape systems (7). It was recognized that the spinal column was the compressive element that pushed the upper body out of the aircraft during ejection. To protect the spine against forces greater than it could withstand, a critical acceleration limit was calculated, based on vertebrae breaking strength data (8).

Payne (5) assumed in the spinal sub-system of his ride-quality model for repeated shocks, that peak spring deflection rather than absolute deflection marked the boundary of human tolerance. He termed this physiological index the "Dynamic Response Index". Stech and Payne (9) assigned specific parameters to the DRI model for use as a predictor of spinal injury during seat ejection, and the resulting guideline was adopted by the USAF in 1971 (10), and by the Air Standardization Coordinating Committee in 1975 (11).

The model consists of a simple linear mass-spring system with damping that is proportional to velocity (see Figure 2),

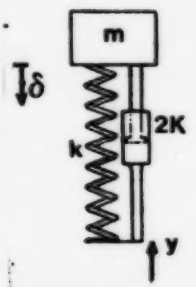

FIGURE 2. Simple linear mass-spring model of the human spine (After Payne (5)).

where k = spring stiffness,
2K = viscous damping constant,
δ = compressive spring deflection,
m = mass, and
y = input displacement of the system (positive upward).

The resulting differential equation for the compressive spring deflection, δ, can be written as:

$$\frac{d^2y}{dt^2} = \frac{d^2\delta}{dt^2} + 2\bar{c}\omega_N \frac{d\delta}{dt} + \omega_N^2\delta$$

$$\frac{\omega_N}{2\pi} = \sqrt{\frac{k}{m}} = 8.4 \text{ Hz}$$

$$\frac{2\bar{c}\omega_N}{2\pi} = \frac{2K}{m} = 3.7 \text{ Hz}$$

where $\bar{c}$ = damping coefficient,
ω_N = the natural frequency, and
$\ddot{y}$ = the acceleration input at the support of the system.

As the system is excited by an acceleration waveform at its support, it will give as an output a corresponding time history of the compressive deflection of the spring. The DRI is related to the peak value of this deflection, δ_{max}, as follows:

$$DRI = \frac{\omega_N^2 \delta_{max}}{g}$$

where the particular damping coefficient for which the DRI is computed is:

$$c = 0.225 \ (5).$$

The DRI is so defined that for a time-invariant value of acceleration at the input of the model, the value of DRI will equal this input acceleration in units of g. Hence, when the static output of a z-axis accelerometer (i.e., 1 g) is fed into the model, the output would yield a constant value of DRI = 1 g.

Most recently, Allen (12) has proposed a specification for human tolerance to repeated shocks, based on the DRI model and on the concept that structural fatigue or damage is cumulatively linear to the point of rupture (Miner's Rule):

Cumulative Damage, $$CD = \Sigma \frac{n_i}{N_i}.$$

where n_i = number of shocks observed at the ith DRI level, and
N_i = number of shocks permitted at the ith DRI level.

It is reasoned that against a given criterion, the body can tolerate a specific number of shocks on any one day, that recovery takes place within that day, and that a similar number of shocks can be tolerated the following day. The higher the amplitude of the shocks, the fewer are the number of tolerable shocks.

For ride quality, Allen's proposal contains exposure limits representing various degrees of discomfort as a function of the number of repeated shocks. The few data available pairing subjective responses to a repeated number of shocks include: (a) vertebrae breaking strength data from which the parameters of the DRI spinal-loading model were defined (DRI = 20 g corresponds to 50 per cent probability of spinal injury (9)); (b) correlation of DRI to operational-ejection injury rates (13); (c) French Mirage III aircraft incidents in which several high acceleration oscillations occurred (14); (d) reputed West German tank crew tolerance limits (15), and (e) Allen's empirical estimates and interpretation of available data (16).

In the proposal, Allen has specified exposure limits representing various degrees of discomfort as a function of the number of repeated shocks: Passenger Comfort (PC) (applicable to the ordinary traveling public), Moderate Discomfort (MD) (acceptable on a daily basis by vehicle/aircraft operators and crew), and Severe Discomfort (SD) (high level shocks causing severe discomfort, which can be accepted daily, but may carry a long term cumulative risk) (see Figure 3). In addition, a five per-cent back-injury criterion (DRI = 16 g) is specified (9). Note that the slope of the criterion line is greater between 1 to 5 shocks per day (for corresponding DRI values of 16 g and 9 g respectively) than at the higher number-of-shocks (dashed line) portion of the criterion. Allen suggests that the increased slope is plausible if the spine is assumed to behave "similar to certain mechanical structural components which are known to stand a high load if it is only applied once but which will fail if a considerably lower load is applied just a few times" (19). Also, a period considerably longer than 24 hours is required for recovery from very high amplitude shocks. Accordingly, the upper curve defines higher amplitude shocks requiring a 100-day recovery period; the lower discomfort curves apply to repeated daily exposures.

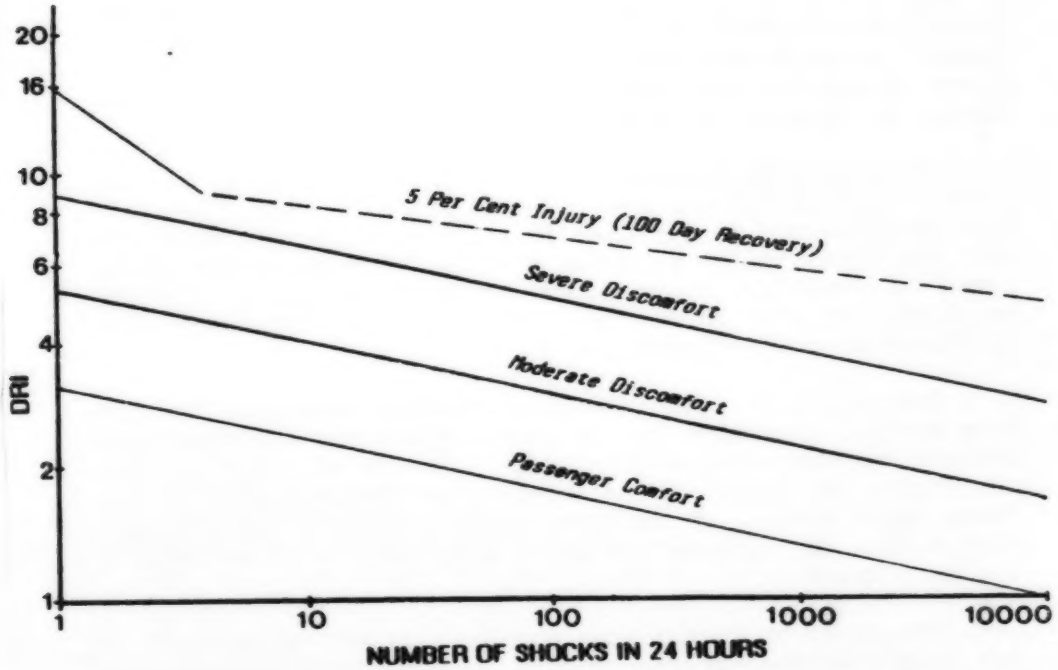

FIGURE 3. Suggested exposure limits representing various degrees of discomfort and a five per-cent back-injury criterion, as a function of Dynamic Response Index (DRI) and number of repeated shocks per day (After Allen (12)).

An electronic analogue of Payne's spinal model has been implemented by the Institute for Aerospace Studies, University of Toronto, under a contract issued by DCIEM, to permit the

evaluation of high crest-factor vibrations (17). In addition to an analogue computer, associated components include signal preconditioning, and timing and sample and hold circuitry.

The z-axis acceleration signal is fed into the spinal-model analogue, either the direct output of a calibrated accelerometer or the analogue recording of the output of a calibrated accelerometer. The computer produces analogue and digital output signals representing the DRI value for each compressive peak in the signal.

The digital output signal is interfaced to a micro-computer which is used to store values of DRI, record the duration of the acceleration signal, and compute accumulated DRI doses in accordance with Miner's Rule for application to Allen's ride quality criteria (18).

ASSESSMENT OF VEHICLE VIBRATION USING THE ISO 2631 AND THE DRI/ALLEN CRITERIA

An analysis of the ride qualities of three Canadian Forces (CF) vehicles was carried out using the ISO 2631 and the Allen/DRI criteria. Accelerations were recorded in the z-axis at the driver's buttocks, as each vehicle was driven at representative speeds over various types of road and terrain. Overall weighted-acceleration levels were computed, from which limits of exposure were determined in accordance with the RC, FDP and EL criteria, as shown in Table I (19,20).

The associated vehicle-ride crest factors in excess of the limit value of 6.0 are also given in Table I. High crest factors were observed in the acceleration samples of the M113 APC and the five-quarter ton truck of 13 and 9 respectively. It is noted that severity, indicated by decreasing exposure duration relative to the three ISO 2631 criteria, increased with acceleration-waveform crest factor.

The results of the DRI-Allen computer analysis of the acceleration histories for the three vehicle/speed/surface conditions are also summarized in Table I. In the M113, the PC and MD boundaries would be exceeded after four minutes and four hours respectively. In the five-quarter ton truck, the PC boundary would be exceeded in three hours and the MD boundary is beyond 24 hours.

The effect of gravity-bias acceleration was suppressed at the output of the analogue computer in accordance with standard practice (10,11). Further, a cut-off was selected arbitrarily such that the digital computer program did not accumulate DRI values for accelerations less than 1 g (DRI< 1.0 g). Accordingly, no values of DRI were generated for the Centurion Tank.

TABLE I

M113 APC, CENTURION TANK, AND FIVE-QUARTER TON TRUCK Z-AXIS EXPOSURE LIMITS AT THE DRIVER'S SEAT, USING ISO 2631 AND ALLEN'S DRI-TOLERANCE CRITERIA, FOR VARIOUS SPEED AND SURFACE CONDITIONS.

VEHICLE SPEED/SURFACE	CREST FACTOR	ISO 2631 RC	ISO 2631 FDP	ISO 2631 EL	DRI/ALLEN PC	DRI/ALLEN MD	DRI/ALLEN SD
M113 APC							
20 kph, cross country (See Note 1)	13	<1min	1hr	4hr	4min	4hr	24hr
FIVE-QUARTER TON TRUCK							
50 kph, rough pavement (See Note 2)	9	25min	4hr	8hr	3hr	24hr	24hr
CENTURION TANK							
12 kph, cross country (See Note 3)	<6	1hr	8hr	24hr			

NOTES:

1. During the 3-minute sample, 12 shocks exceeding 1 Gz were observed, producing values of DRI ranging from 1.01 g to 2.79 g, with a mean value of 1.65 g and a standard deviation of 0.56 g.

2. During the 7-minute sample, 22 shocks exceeding 1 Gz were observed, producing values of DRI ranging from 1.01 g to 1.84 g, with a mean value of 1.26 g and a standard deviation of 0.22 g.

3. The tank cross-country data did not contain acceleration shocks exceeding 1 Gz. Hence, no values of DRI were generated.

DISCUSSION

The exposure-limit values given in Table I must be viewed with caution. When vibration-waveform crest factors exceed 6.0, the effects of the vibration may be underestimated by ISO 2631 (1). More important, the time-dependency assumption in the standard is not supported by experimental data. When the first edition was drafted, very little evidence existed to support the dependence of physiological tolerance, fatigue, and comfort limits on vibration exposure time (21). Even before the standard was published, a review of the literature led Maslen to conclude than "on the whole, in experiments where proper controls have been used, efficiency is almost independent of the duration of the vibration" (22). Subsequent studies have supported this contention for such tasks as tracking, vigilance, visual search,

and handwriting (23,24).

Certain of the simplifying assumptions in the DRI model and the Allen criteria are also questionable. It is assumed, for example, that discomfort is caused solely by the dynamic compression peak loads in the spinal column, whereas discomfort is subjective and often due to non-specific stress. A second assumption, that spinal-column loads are adequately quantified by the DRI, is disputable since spinal-column stiffness is not independent of load level. Data are required to determine if the variable stiffness of the spinal column causes significant discrepancies in subjective responses to a given DRI value.

A third assumption, that damage is a linear function of accumulated loads, also requires validation, since Allen's proposed criteria might be invalidated by non-linear effects. There may be, for example, a discontinuity in the relationship between acceptable levels and number of shocks at higher amplitudes, analogous to the critical level observed in noise-induced hearing threshold shift or the yield point in metal and structural fatigue.

Sandover has suggested that the relationship between the applied stress and the number of cycles to fatigue-induced vertebral failure may be an exponential function (25). If so, an increase in dynamic stress is more important than a corresponding increase in duration of exposure, and current methods of vibration measurement underestimate the risk of injury if the vibration contains significant peaks.

Griffin and Whitham (26) have applied root-mean-quad (rmq) (fourth-power equivalent to rms) measures of acceleration to predict subjective intensity. However, Sandover questions whether rmq measures of acceleration differentiate between vehicle/terrain ride characteristics any better than rms measures at the moderate crest factors (e.g., between 6 and 15) encountered in many vehicle-ride environments.

In addition, a question exists concerning the significance of input accelerations that generate values of DRI less than 1 g (27). Although such values were not used in this study to determine the cumulative PC and MD limits in Table I, as stated, their effects upon soft-body tissue may be an important factor in ride-discomfort analysis, particularly since the present DRI method of assessing the effect of shocks is thought to underestimate the effects of a great number of shocks of low intensity (28).

In spite of the utility of the simple biodynamic model, Payne's compressive model of the spine may be insufficient to explain completely vibration stress in the lumbar spine. Sandover (25) suggests that vertical-axis vibration can induce a rocking motion of the pelvis that produces forces at the intervertebral end plates or loads on the annulus that are at least as significant a factor as simple spinal compression in fatigue-induced pathology (29).

Recently, Brinkley (30) has reported on a design approach to ejection-seat impulse acceleration exposure limits in the three translational and rotational axes. Dynamic-response models have been proposed for each orthogonal axis, similar to the simple z-axis mass-spring-damper system of Payne (5), with coefficients chosen to agree with available data.

In view of the foregoing discussion, the question to be addressed is whether the proposed DRI/Allen technique is sufficiently meaningful for assessing human tolerance to repeated mechanical shocks, particularly when such shocks occur frequently and at low intensities.

With respect to absolute exposure limits, one would expect Allen's Severe Discomfort criterion to be more restrictive than the ISO 2631 Exposure Limit when waveform crest factors exceed 6.0. In this study the opposite was observed; the ISO 2631 Exposure Limits are more restrictive by factors of at least six to one. This may be attributable to a number of factors: differences and/or uncertainties in the time-dependency assumptions in the two criteria, the simplifying assumptions in the DRI model and Allen's proposed criteria, and/or the relatively low intensity of the mechanical shocks encountered in the vehicle rides studied. Suffice it to say that before the DRI spinal model and Allen's proposed criteria can be used as a robust method of evaluating vehicle ride quality, considerably more data are required relating observed human tolerance to repeated mechanical shocks.

There is nothing to suggest that the procedure should not be used to assess relative ride quality. In this study, both the Allen and the ISO 2631 criteria rank the three vehicle/speed/surface conditions in the same order, supporting the findings of Beevis and Forshaw*. Since the two criteria are based on different biodynamic models, however, differences in rankings might be expected in a large and varied sample of vehicle/surface conditions. A limited theoretical comparison of Allen's Severe Discomfort criteria and the ISO 2631 Exposure Limit suggests that any "compatibility" between the two may be restricted to crest factors in the range 3.7 to 5.0 (12). Additional data are required to clarify these questions.

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* M113 APC drivers who drove routinely on off-road surfaces at CFB Gagetown for periods far in excess of the ISO 2631 Exposure Limits were observed to experience a higher incidence of lower back pain than did Centurion Tank drivers with about the same accumulated time on off-road surfaces, and more than APC drivers who spent fewer hours driving per week, almost entirely on gravel roads. Is is noted, however, that poor driving posture is considered the significant source of back pathology in crews of CF armoured fighting vehicles; high levels of vibration are thought simply to exacerbate the problem (31).

CONCLUSIONS

1. More data are required on the observed effects of human exposure to mechanical shocks, particularly when they occur at relatively low intensities, before Payne's DRI model and Allen's proposed comfort and injury criteria can be used as a robust method to assess human tolerance to such shocks.

2. The significance of input accelerations that generate values of DRI less than 1 g is uncertain. Although such values were not used in the present study, their effects upon ride comfort should be studied.

3. Although both the DRI/Allen procedure and ISO Standard 2631 ranked the three vehicle/surface conditions studied in the same order, studies involving a much wider variety of conditions should be conducted to determine possible differences between the two.

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